The CNGS Neutrino Beam

G. GIACOMELLI
Dept of Physics, Univ. of Bologna and INFN,
V.le C. Berti Pichat 6/2, Bologna, I-40127, Italy
E-mail: giacomelli@bo.infn.it

Lecture given at the 2^{nd} Latin American School on Cosmic Rays and Astrophysics, Puebla, Mexico, 30^{th} August - 8^{th} September 2006.

Abstract

The CERN to Gran Sasso Neutrino beam (CNGS) was commissioned at CERN in early August 2006 and was first sent at low intensity to Gran Sasso on August 17, 2006. The Borexino, LVD and OPERA detectors continued the commissioning of their detectors and started taking data with practically no dead time. The CNGS operated smoothly with good quality. In a short time the 3 detectors collected several hundred events with clean time distributions.

1 Introduction

Neutrino physics has opened new windows into phenomena beyond the Standard Model of particle physics. Long baseline neutrino experiments may allow further insight into neutrino physics. The CERN to Gran Sasso neutrino beam (CNGS) is one of these projects [1]; it was commissioned at CERN in early august 2006 and it started sending beam to the Gran Sasso Lab. (LNGS) on the 17^{th} of August 2006. At Gran Sasso 3 detectors, Borexino, LVD and OPERA, were ready to use it, and imediately started to see beam neutrino events.

OPERA [2] is a hybrid-emulsion-electronic detector, designed to search for the $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations in the parameter region indicated by the MACRO [3], SuperKamiokande [4] and Soudan2 [5] atmospheric neutrino results [6], recently confirmed by the K2K [7] and MINOS [8] long baseline experiments. One of the main goals of OPERA is to find the ν_τ appearance by direct detection of the τ lepton from ν_τ CC interactions. The detection of the ν_τ will be made via the charged τ lepton produced in ν_τ CC interactions, and its decay products. To observe the decays, a spatial resolution of ~ 1 μm is necessary; this resolution is obtained in emulsion sheets interspersed with thin lead target plates. This technique, the "Emulsion Cloud Chamber" (ECC), was started in the τ search experiment [9]. OPERA may also search for the subleading $\nu_\mu \longleftrightarrow \nu_e$ oscillations and make a variety of observations with or without the beam using its electronic subdetectors.

LVD is an array of 840 liquid scintillators with a total mass of 1000 t; it is designed to search and study neutrinos from gravitational stellar collapses [10]. LVD plans to be a neutrino flux monitor of the CNGS beam.

Borexino is a refined electronic detector designed to study solar neutrinos, in particular the monoenergetic neutrinos coming from Be^7 decay [11]. In August 2006 it was only partially filled with water: now it is completely filled with water and its inner part is partially filled with liquid scintillator.

In this lecture note will be summarized and discussed the CNGS neutrino beam, some features of the Borexino, LVD, and OPERA experiments, and the preliminary results obtained by the three experiments during the August 2006 test run.

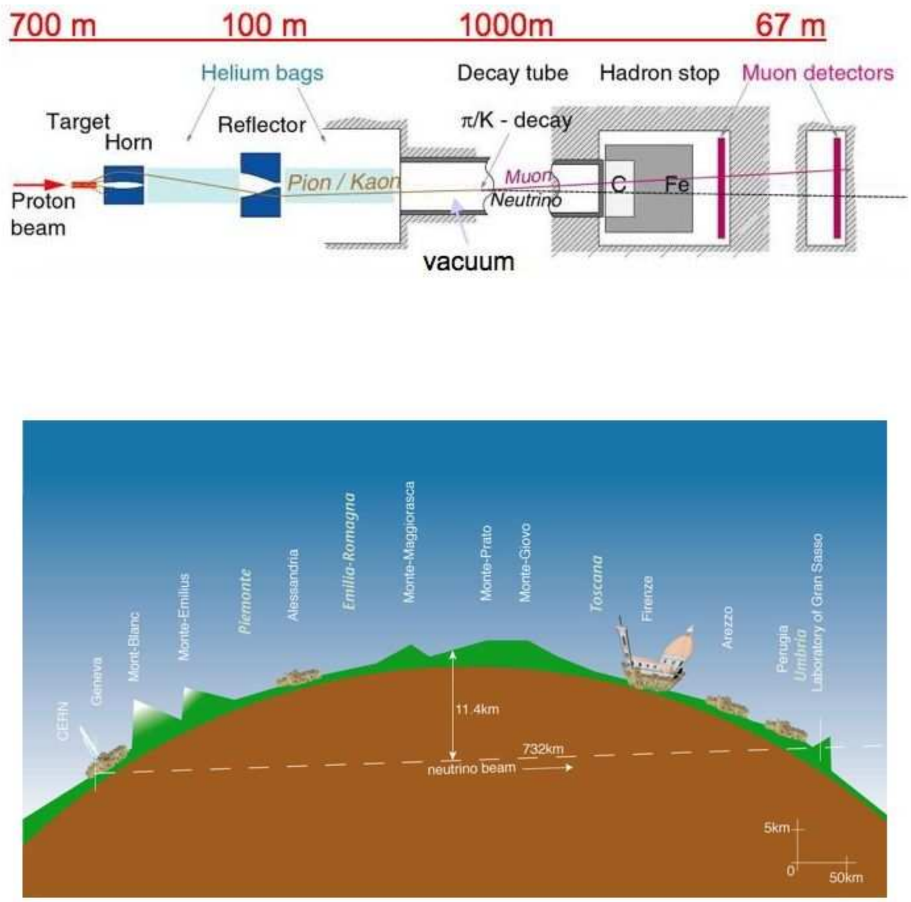

Figure 1: Top: The main components of the CNGS neutrino beam at CERN. Bottom: Sketch of the 730 km neutrino trajectory from CERN to Gran Sasso.

2 The CNGS neutrino beam

Fig. 1 top shows the main components of the ν_μ beam at CERN [1]. A 400 GeV proton beam is extracted from the SPS and is transported to the CNGS target. Secondary pions and kaons of positive charge are focused into a parallel beam by two magnetic lenses, called horn and reflector. A long decay pipe allows the pions and kaons to decay into ν_μ and μ. The remaining hadrons are absorbed in a beam dump. The muons are monitored by two sets of detectors downstream of the dump.

Fig. 1 bottom shows the 730 km path of the CNGS neutrinos from CERN to Gran Sasso. The beam is optimised for producing a maximum number of CC ν_τ interactions in OPERA at Gran Sasso. Fig. 2 left shows the underground layout of the SPS and of CNGS at CERN; Fig. 2 right shows the scheme of the SPS operation during the August 2006 test run. The energy distribution of the beam at Gran Sasso is shown in Fig. 3: the mean ν_μ beam energy is 17 GeV, the $\bar{\nu_\mu}$ contamination is $\sim$2%, the ν_e ($\bar{\nu_e}$) is $< 1\%$ and the number of ν_τ is negligible. The L/E_ν ratio is 43 km/GeV. The muon beam size at the second muon detector at CERN is about $\sigma \sim$1 m; this translates into a neutrino beam size at GS of

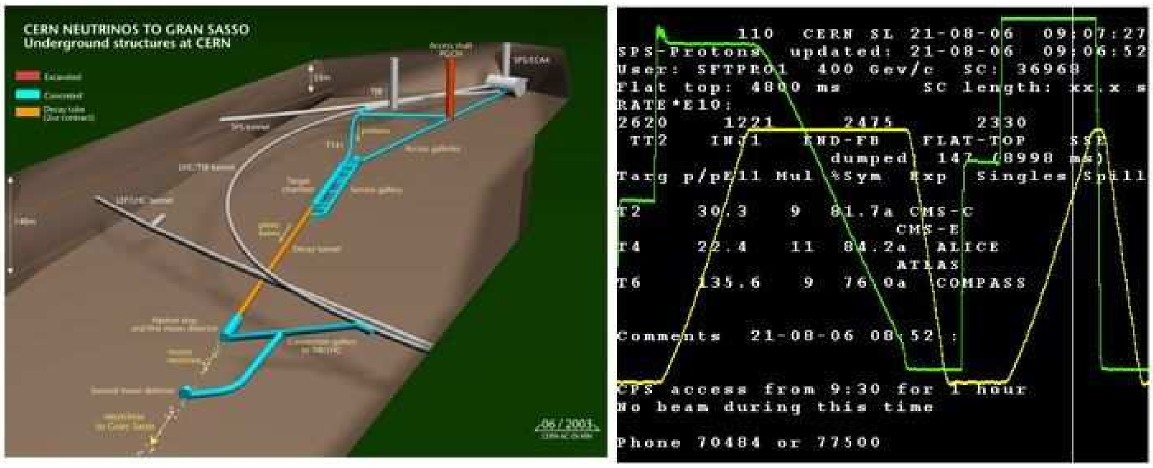

Figure 2: Left: Underground layout of the SPS and of the CNGS beam at CERN. Right: Scheme of the SPS operation at CERN during the August test run.

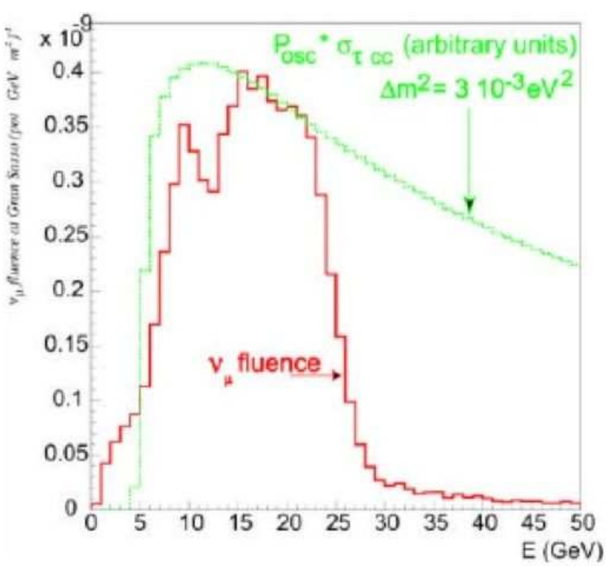

Figure 3: Energy distribution of the CNGS ν_μ beam at Gran Sasso.

σ ~1 km. Civil engineering was completed in june 2006, all beam parts were installed and commissioning was made in early August. The first low intensity test beam was expected at GS in August 17 2006: this happened, and almost immediately the 3 detectors at GS obtained their first events (Figs. 6, 10). The low intensity CNGS was stable and of high quality. The shared SPS beam sent a pulse of 2 neutrino bursts, each of 10.5 μsec duration, separated by 50 ms, every 12 s [1]. A higher intensity beam was expected for October 2006, but it did not happen because of a water leak in the beam at CERN.

3 BOREXINO

The main aim of the BOREXINO detector is the measurement of the monochromatic ν_e's coming from Be^7 decays in the center of the sun. The layout of BOREXINO in Hall C is shown in Fig. 4 [11]. The most important part of the detector is the large sphere, whose central part should be filled with liquid scintillator. The outer sphere should be filled with pure water. The filling with water was started in early August and during the first run only few meters of water were in the sphere. The partial filling limited the data acquisition. Nevertheless 5 neutrino candidate events were observed. In December 2006 the water filling was completed and initial filling with liquid scintillator in the inner sphere was started.

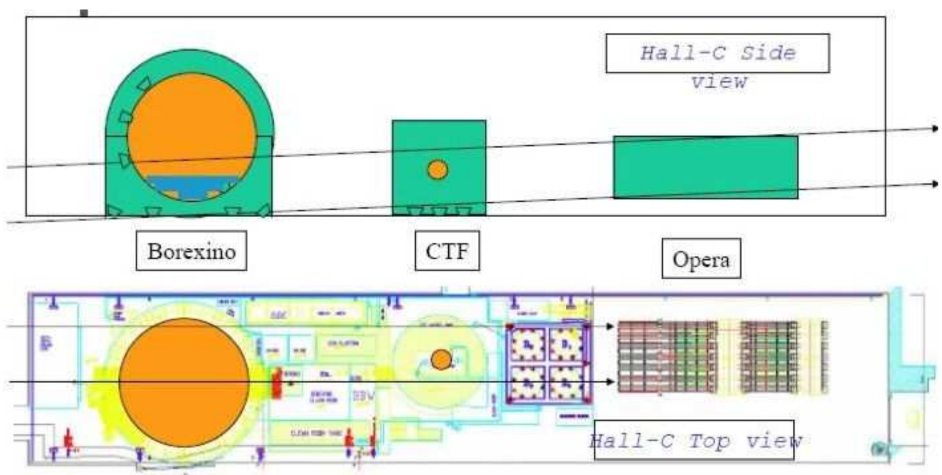

Figure 4: Layout of the Borexino and OPERA experiments in Hall C of the underground Gran Sasso Lab. Side view of Hall C (upper figure) and view from the top (lower figure).

4 LVD

The main purpose of the LVD detector is the search for electron antineutrinos from gravitational stellar collapses in our galaxy. LVD is made of three identical "towers", each containing 8 active modules; a module has 8 counters of dimension $1 \times 1 \times 1.5\ m^3$, filled with 1.2 t of liquid scintillator. Fig. 5 shows the LVD detector located in Hall A of Gran Sasso; it has a total mass of 1000 t [10]. Neutrinos from the CNGS beam are observed through: (i) the detection of muons produced in neutrino CC interactions in the surrounding rock or in the detector, (ii) through the detection of the hadrons produced in neutrino NC/CC interactions inside the detector.

LVD plans to be a neutrino flux monitor of CNGS at Gran Sasso. Since LVD is running since several years, it was completely ready when the neutrino beam arrived. Fig. 6a shows a muon coming from a ν_μ interaction in the rock before the detector; Fig. 6b shows a ν_μ NC/CC interaction inside the detector. In the August 2006 test run LVD was counting 50-100 muons per day and recorded a total of about 500 events [10].

Figure 5: The LVD detector in the Gran Sasso Hall A.

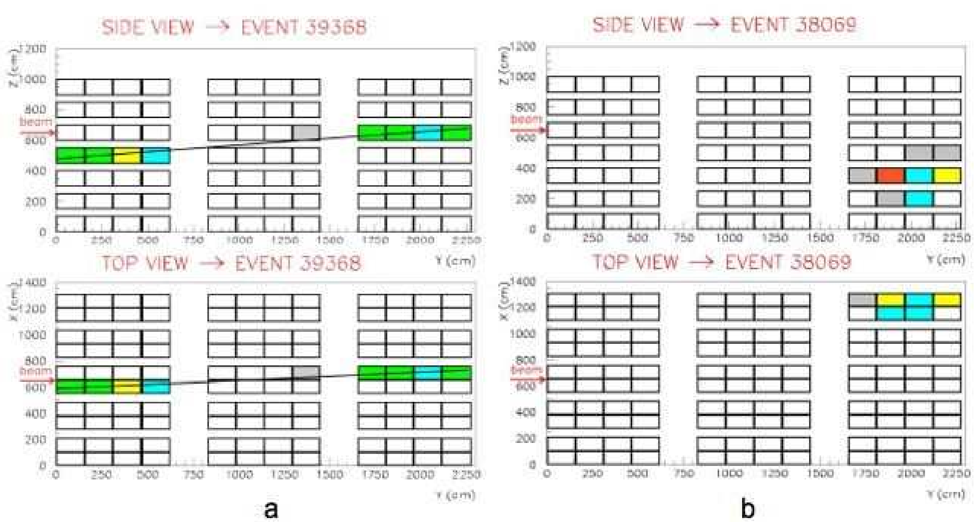

Figure 6: Observation in LVD of (a) one muon originated in a ν_μ CC interaction in the rock before the detector; (b) a multihadron event originated by a ν_μ NC/CC interaction inside the detector.

5 OPERA

The OPERA detector, Fig. 7, is a hybrid detector made of two identical supermodules, each consisting of a target section with 31 target planes of lead/emulsion-film modules ("bricks"), of a scintillator tracker detector and of a muon spectrometer. The initial target mass should be 1.8 kt. It is the first detector specifically designed for the CNGS ν beam.

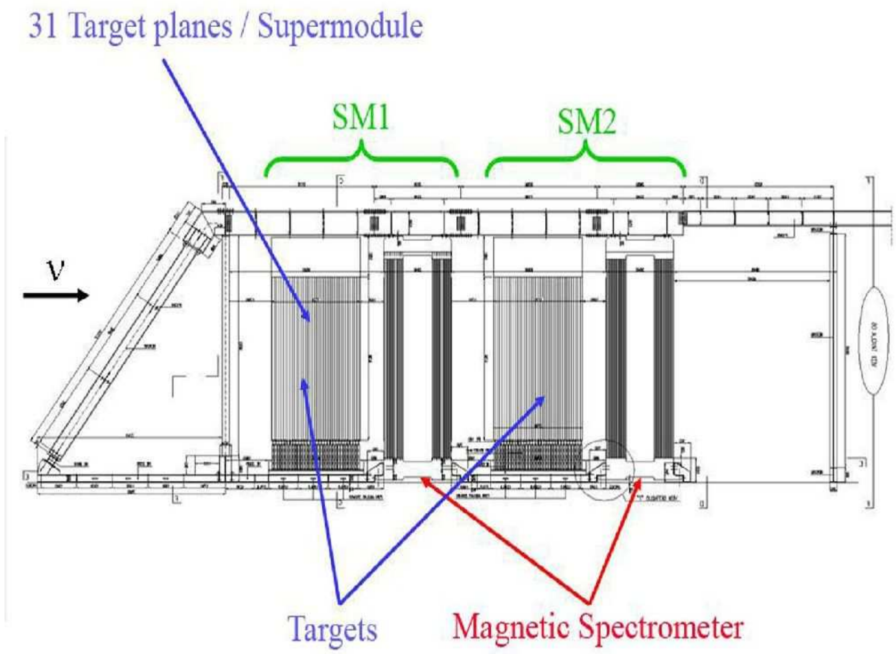

Figure 7: Layout of the OPERA detector.

Electronic subdetectors. The first electronic subdetector is an *anticoincidence wall* to better separate muon events coming from interactions in OPERA from those in the material and rock before OPERA.

The *target tracker* is made of 32000 scintillator strips, each 7 m long and of 25 mm$\times$15 mm cross section (7000 m^2 area). Along the strip, a wavelength shifting fibre of 1 mm diameter transmits the light signals to both ends. The readout is done by 1000 64 channel Hamamatsu PhotoMultipliers (PMTs).

The *muon spectrometer* consists of 2 iron magnets instrumented with *Resistive Plate Chambers* (RPC) and *drift tubes*. Each magnet is an 8×8 m^2 dipole with a field of 1.52 T in the upward direction on one side and in the downward direction on the other side. This allows to measure the momentum twice, reducing the error by $\sqrt{2}$. A magnet consists of twelve 5 cm thick iron slabs, alternated with RPC planes. In the magnetic field a muon is tracked, identified and its momentum is measured.

The *precision tracker* [12] measures the muon track coordinates in the horizontal plane. It is made of 12 drift tube planes, each covering an area of 8×8 m^2; they are placed in front and behind each magnet and between the two magnets. The muon spectrometer allows a momentum resolution $\Delta p/p \leq 0.25$ for muon momenta < 25 GeV/c. Two planes of *glass RPC's (XPC's)*, consisting of two 45° crossed planes, are installed in front of the magnets.

In August 2006 the brick supporting structure, the tracker planes, the XPC's and three of the high precision tracker planes of the first supermodule were installed. The magnets, including all RPC's and the mechanical structure were completed.

The DAQ system uses a Gigabit network of 1150 nodes. To match the data of the different subdetectors an event "time stamp" is delivered by a clock using the Global Positioning System (GPS). The synchronization with the beam spill is done via GPS. The DAQ uses a system which contains the CPU, the memory, the clock receiver for the time stamp and the ethernet connections to the other components.

The commissioning of each electronic subdetector was made first with cosmic ray muons and then with the CNGS at reduced intensity in August 2006.

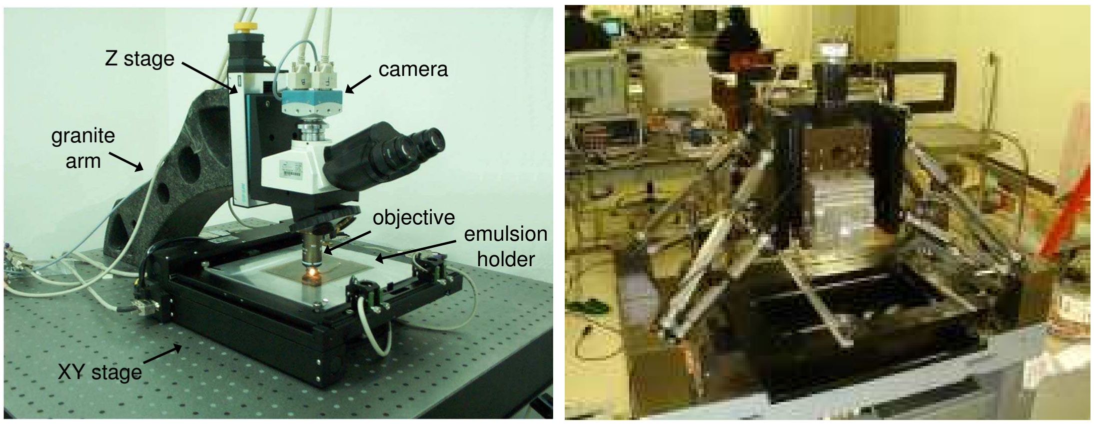

Figure 8: Photograph of one of the ESS microscopes (left) and of the S-UTS (right).

Nuclear emulsions and their scanning. The basic target module is a *"brick"*, consisting of a sequence of 56 lead plates (1 mm thick) and 57 emulsion layers. A brick has a size of 10.2×12.7 cm^2, a depth of 7.5 cm (10 radiation lengths) and a weight of 8.3 kg. Two additional emulsion sheets, the *changeable sheets* (CS), are glued on its downstream face. The bricks are arranged in walls. Within a brick, the achieved spatial resolution is < 1 μm and the angular resolution is $\sim$2 mrad. To provide a ν interaction trigger and to identify the brick in which the interaction took place, the brick walls are complemented by walls of target trackers and a muon spectrometer [15].

The bricks are made by the *Brick Assembling Machine* (BAM), which consists of robots for the mechanical packing of the bricks. The BAM is installed in the Gran Sasso lab and it may produce $\sim$ 1 brick every 1-2 minutes. The bricks are handled by the *Brick Manipulator System* (BMS), made of two robots, each operating at one side of the detector. An arm is used to insert the bricks. The extraction of a brick, in the region indicated by the electronic detectors, is done by a vacuum sucker of the BMS.

A fast automated scanning system is needed to cope with the daily analysis of a large number of emulsion sheets. The minimum required scanning speed is $\sim$ 20 cm^2/h per emulsion layer (44 μm thick). It corresponds to an increase in speed of one order of magnitude with respect to past systems [13, 14]. For this purpose were developed the *European Scanning System* (ESS) in Europe [16] and the *S-UTS* in Japan [17].

The main components of the ESS microscope are shown in Fig. 8 left: (i) a high quality, rigid and vibration-free support table; (ii) a motor driven scanning stage for horizontal (XY) motion; (iii) a granite arm; (iv) a motor driven stage mounted vertically (Z) on the granite arm for focusing; (v) optics; (vi) digital camera for image grabbing mounted on the vertical stage; (vii) an illumination system. The emulsion is placed on a glass plate (emulsion holder) and its flatness is guaranteed by a vacuum system. By adjusting the focal plane of the objective, the 44 μm emulsion thickness is spanned and 16 tomographic images of each field of view are taken at equally spaced depths. The images are digitized, converted into a grey scale of 256 levels, sent to a vision processor board and analyzed to recognize

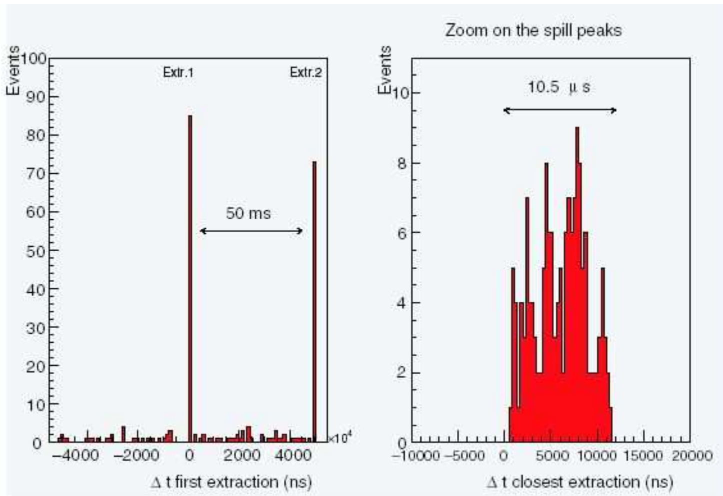

Figure 9: Time distribution of muon events collected by OPERA in the CNGS neutrino test run. The muon event time difference with respect to the closest extraction is shown in the right histogram.

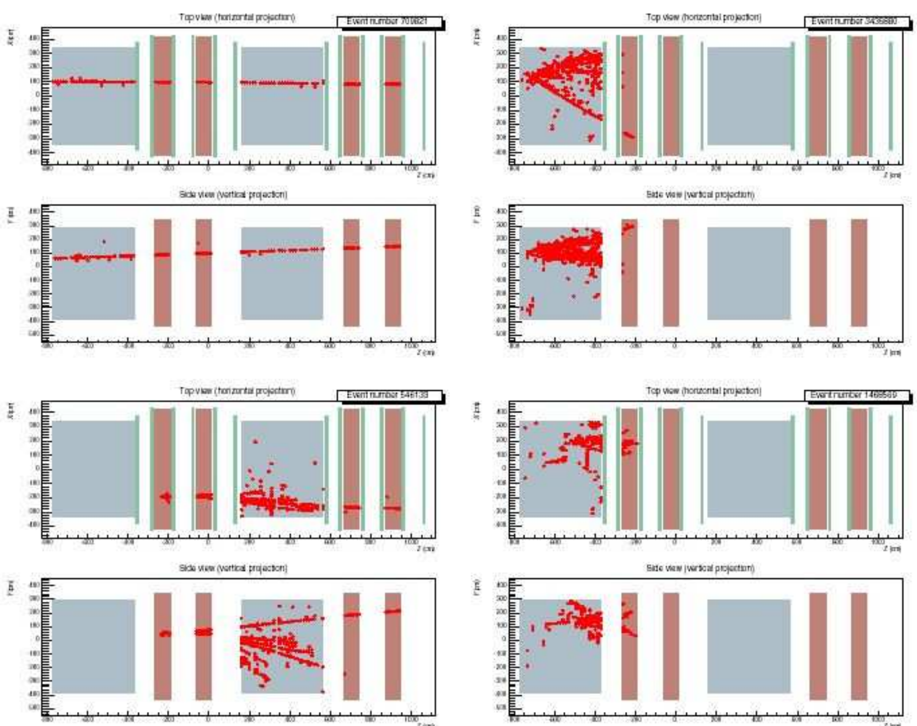

Figure 10: Display of OPERA neutrino muon events from the CNGS test run. For each event the top and side views are shown, respectively. The targets are indicated in blue, the spectrometers in light brown, Target Tracker and RPC hits in red. Top left: ν_μ CC interaction in the rock upstream of the detector; top-right and bottom-right: ν_μ CC and NC interactions in the target material; bottom-left: ν_μ CC interaction in the iron of the spectrometer.

sequences of aligned grains. The three-dimensional structure of a track in an emulsion layer (*microtrack*) is reconstructed by combining clusters belonging to images at different levels. Each microtrack pair is connected across the plastic base to form the *base track*. A set of connected base tracks forms a *volume track*. The Japanese S-UTS system, Fig. 8 right, is based on hardware designed and made in Nagoya; the software system is mounted in specially designed electronic boards.

6 The first test run with CNGS neutrinos. Conclusions

A detailed description of the CNGS operation during the August test run may be found in [1]. During this run an integrated intensity of 7.6×10^{17} p.o.t. was delivered. The accuracy in the time synchronization between CERN and Gran Sasso was better than 100 ns. The beam time spill is shown in Fig. 9. Event samples recorded by LVD and OPERA are shown in Figs. 6 and 10, respectively.

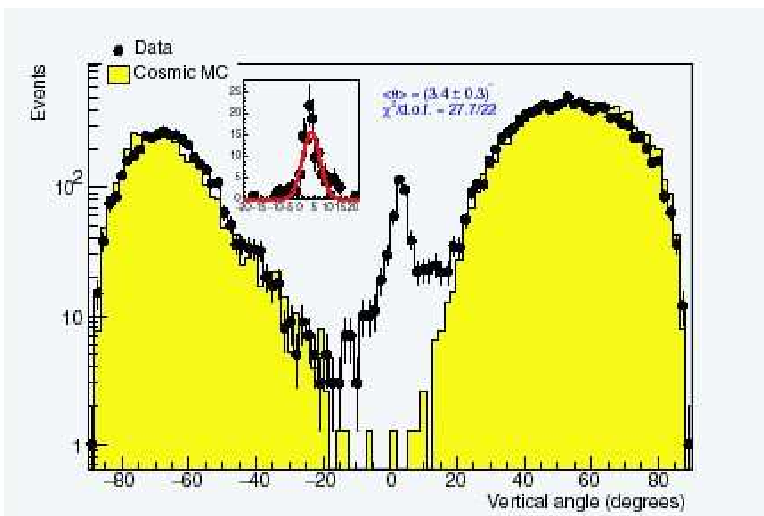

Figure 11: Angular distribution of CNGS beam-induced muons and cosmic-muon events taken with the electronic detectors (black points). The histogram is the prediction from cosmic simulations. The inset shows the on-time beam muon events.

OPERA recorded 319 neutrino events, consistent with the 300 events expected on the basis of the delivered integrated intensity. The θ angular distribution with respect to the horizontal axis is shown in Fig. 11. In the same figure, the distribution of simulated cosmic-ray muons is also shown. In the inset is shown the angular distribution of beam events; a Gaussian fit to the θ angle distribution of these events on-time with the beam yielded a mean muon angle of $3.4°$ in agreement with the value of $3.3°$, expected for neutrinos originating from CERN and travelling under the earth surface to the LNGS underground halls.

During the August test run a succesful test of the CS procedure was performed by using an emulsion detector plane consisting of a matrix of 15×20 individual CS doublets inserted in the SM2 target. 9 muons produced by neutrino interactions in the rock surrounding the detector crossed the CS plane surface; most of them were found by scanning the emulsion

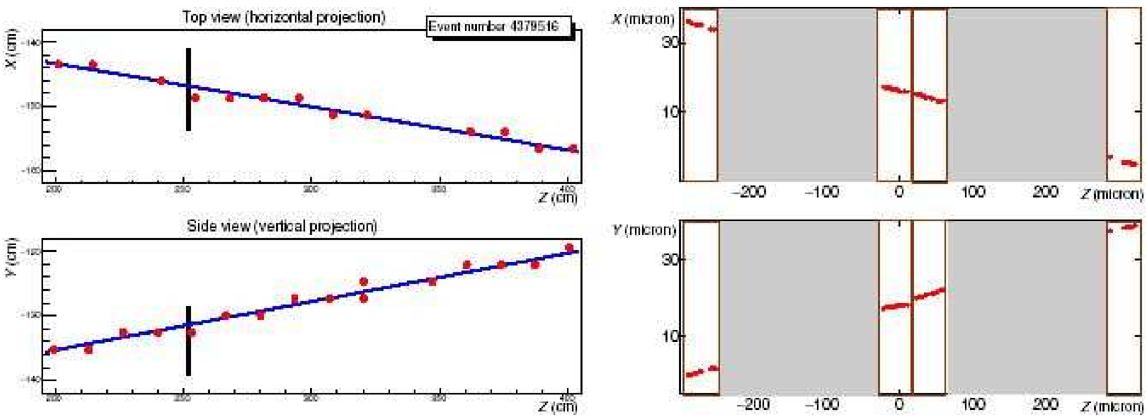

Figure 12: Left: display of one event with the muon passing through electronic detectors and (right) the corresponding four microtracks in the "changeable sheets" emulsion doublet.

films, see Fig 12. The test proved the capability in passing from the centimetre scale of the electronic tracker resolution to the micrometric resolution of nuclear emulsions.

In conclusion the CNGS neutrino beam performed well in the first test run. And the Borexino, LVD and OPERA experiments at Gran Sasso recorded a number of events.

In particular OPERA recorded 319 muon events in agreement with expectations. The reconstructed zenith-angle distribution from muon tracks in centered at 3.4°, as expected for neutrinos originating at CERN and travelling under the earth surface to LNGS. A test of the association between muon tracks reconstructed by electronic detectors and with emulsions was successfully performed, proving the capability of passing from the centimeter scale of electronic detectors to the micron scale of nuclear emulsions.

I would like to acknowledge the cooperation of the CNGS team at CERN, of the LNGS staff, and of the Borexino, LVD and OPERA experiments. I thank Ms. A. Casoni for typing the manuscript and Dr. M. Giorgini for advice.

References

[1] CNGS project: http://proj-cngs.web.cern.ch/proj-cngs/.

[2] http://operaweb.web.cern.ch/. Acquafredda, R. et al.: 2006 *J. Phys.* **8**, 303, hep-ex/0611023.

[3] Ahlen, S.P. et al.: 1995, *Phys. Lett.* **B449**, 481. Ambrosio, M. et al.: 1998, *Phys. Lett.* **B434**, 451; 2000, *Phys. Lett.* **B478**, 5; 2003, *Phys. Lett.* **B566**, 35; 2004, *Eur. Phys. J.* **C36**, 323.

[4] Fukuda, Y. et al.: 1998, *Phys. Rev. Lett.* **81**; 1562. Ashie, Y. et al.: 2004, *Phys. Rev. Lett.* **93**; 101801. Hosaka, J. et al.: 2006, *Phys. Rev* **D74**, 032002.

[5] Allison, W. W. et al.: 1999, *Phys. Lett.* **B449**, 137; 2005, *Phys. Rev.* **D72**, 052005.

[6] Giacomelli, G. et al.: 2005, hep-ex/0504002; hep-ex/0407023.

[7] Kielczewska, D. et al.: 2004, *Acta Phys. Polon.* **B35**, 1933.

[8] Tagg, N. for the MINOS Coll.: 2006, hep-ex/0605058.

[9] Kodama, K. et al.: 2001, *Phys. Lett.* **B504**, 218.

[10] http://www.bo.infn.it/lvd. Menghetti, H. (LVD presentation) 22/08/06 Gran Sasso meeting.

[11] http://borex.lngs.infn.it. Pallavicini, M. (A few CNGS events in Borexino) Gran Sasso meeting.

[12] http://operaweb.web.cern.ch/operaweb/detector/components/index.shtml. Zimmermann, R. et al.: 2005, *Nucl. Instr. Meth.* **A555**, 435.

[13] Aoki, S. et al.: 1990, *Nucl. Instr. Meth.* **B51**, 466.

[14] D'Ambrosio, N. et al.: 2004, *Nucl. Instr. Meth.* **525**, 193.

[15] Giacomelli, G. et al.: physics/0609045.

[16] Armenise, N. et al.: 2005, *Nucl. Instr. Meth.* **A551**, 261. De Serio, M. et al.: 2005, *Nucl. Instr. Meth.* **A554**, 247. Arrabito, L. et al.: 2006, physics/0604043, *Nucl. Instr. Meth.* **A568**, 578; physics/0701192.

[17] Nakano, T.: Proc. of Int. Europhys. Conf. on High Energy Physics, Budapest, Hungary, 2001.